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Challenges in Developing the Microwave Instrument for the Rosetta Orbiter

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Abstract - The Microwave Instrument for the Rosetta Orbiter (MIRO) built by the Jet Propulsion Laboratory, will be launched on the European Space Agency's (ESA) ROSETTA Spacecraft in 2004. MIRO will measure the near surface temperatures of the asteroids OTAWARA and SIWA, and the comet WIRTANEN, thereby allowing scientists to estimate the thermal and electrical properties of these surfaces. The MIRO instrument consists of two heterodyne radiometers, one operating at millimeter wavelengths (190 GHz, ~1.6 mm) and one operating at submillimeter wavelengths (562 GHz, ~0.5 mm). The spectrometer portion of MIRO will allow measurements of water, carbon monoxide, ammonia, and methanol in the gaseous coma of comet WIRTANEN. These measurements will allow scientists to study how the comet material sublimates (changes from its frozen state, ice, to a gas) in time and distance from the sun. As an international team, significant challenges to development and integration coordination were required to ensure instrument delivery to the European Space Agency (ESA). Additionally, the instrument, developed under NASA's Faster, Better, Cheaper paradigm challenged the team to find new and inventive ways to achieve the scientific requirements. This paper will explore the various trades, challenges, processes and programmatic issues encountered.

1. INTRODUCTION

The Microwave Instrument for the Rosetta Orbiter (MIRO) instrument will provide both very sensitive continuum capability for temperature determination and extremely high-resolution spectroscopy for observation of molecular species. The instrument is a two heterodyne receiver system, one at millimeter wavelengths (1.3 mm) and one at submillimeter wavelengths (0.5 mm). The millimeter and the submillimeter radiometers have continuum bandwidths of 0.5 GHz and 1.0 GHz respectively. In addition, the submillimeter receiver has a total spectroscopic bandwidth of 180 MHz and a spectral resolution of 44 kHz. In the spectroscopic mode, there are 4096 channels, each having a bandwidth of 44 kHz that are observed simultaneously.

MIRO started in 1995 with a joint Proposal to ESA and NASA submitted by JPL. The proposal was in response to an Announcement of Opportunity (ESA RO-EST-AO-000). It started as a science collaboration between 19 individuals from 6 different institutions. The MIRO hardware was developed as a partnership among three organizations – the Jet Propulsion Laboratory (JPL) , the Max Planck Institut fur Aeronomie (MPAe) in Germany, and the Observatoire de Paris in France. A functional block diagram for MIRO is shown in Figure 1. This diagram not only indicates the major assembly blocks for the instrument but also identifies the contributing partner. All of the hardware resides inside the ROSETTA spacecraft with the exception of the telescope and baseplate assemblies. The telescope is completely exposed to the space environment and the baseplate is the interface mounting plate to the ROSETTA spacecraft structure for the Sensor Unit.

2. HARDWARE DESCRIPTION[1]

MIRO consists of four units – the Sensor Unit, the Sensor Backend Electronics Unit, the Electronics Unit and the Ultrastable Oscillator Unit. Descriptions of the major functional pieces are described below along with a brief operational mode discussion.

Telescope

The telescope design is optimised to meet the MIRO requirements. The parabolic primary mirror has a diameter of 30 cm, providing a diffraction-limited half-power main beamwidth of about 8 arc min at 560 GHz frequency (0.535 mm wavelength) and about 22 arc min at 188 GHz (1.6 mm wavelength). An offset Cassegrain design is used to minimize volume and provide very low level sidelobes. The flight telescope mounted on the baseplate is shown in Figure 2. The end-to-end optical system is designed to minimise alignment sensitivity to the large temperature range the telescope will experience during the course of the mission.

A significant advantage of the offset Cassegrain design is the absence of aperture blockage and the resulting improvement in both aperture and beam efficiency. The

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[1]MIRO Experiment Interface Document, Part B, 14 May 2001

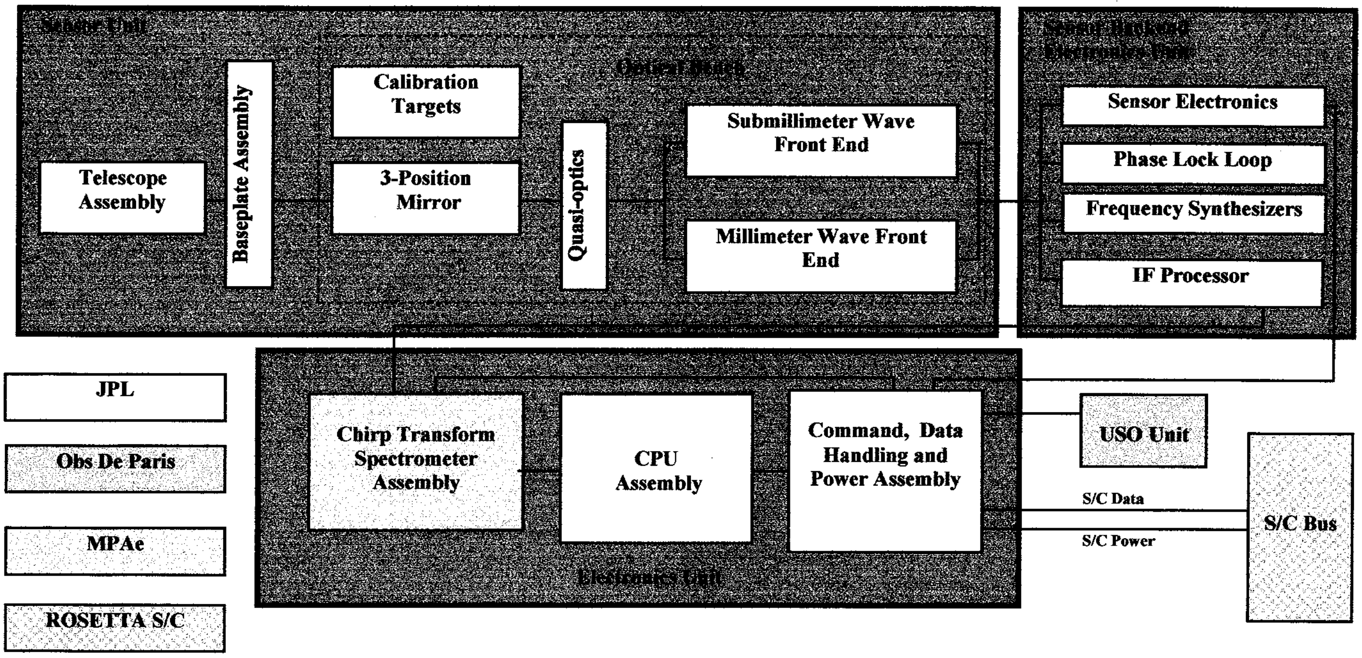


Figure 1 MIRO Functional Block Diagram

efficiency of the telescope is also a function of the mirror surface accuracy. The surface RMS is 11 μm corresponding to less than λ/48 at 0.535 mm. Combining the effects of the illumination, surface error, and reflectivity losses, the telescope has an aperture efficiency of greater than 0.7 and a main beam efficiency of greater than 0.92 at both frequencies.

Another advantage of the offset Cassegrain design is the high quality spectral baseline that it allows for a heterodyne receiver. This is a result of the elimination of the multiple reflections between the receiver input and the secondary mirror, which is a major problem with on-axis systems.

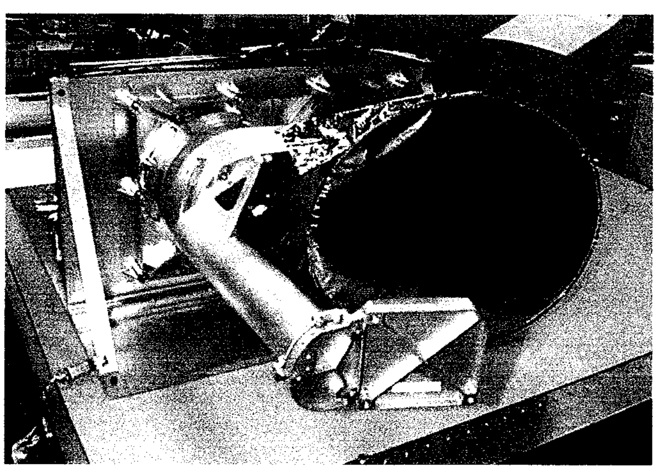


Figure 2 Flight Telescope on Baseplate

Calibration System

The calibration of the instrument is critical and must provide the gain of the system, as well as compensate for systematic variations arising from both long- and short-term drifts and from baseline ripple. The absolute calibration is obtained by observing two blackbody targets at two different temperatures. One target is exposed to space, while the other target is mounted inside the spacecraft at a nominal temperature of 300 K. A temperature difference will be maintained between the targets that is large enough to permit accurate calibration of the receivers in a few minutes of integration time. A mechanical calibration turning mirror, shown as part of the optical bench drawing in Figure 3, directs the beam to observe the telescope, the cold target, or the warm target. This beam switch mirror is the only moving mechanical part of the system.

For spectroscopic observations, the submillimeter wave receiver is operated in a "frequency switched" mode to eliminate residual baseline ripple. For half the integration time, the signal frequency is shifted 5 MHz above the nominal frequency, while the other half of the time it will be shifted 5 MHz below. The frequency switching occurs at a commandable interval in the range of 1 to 5 seconds, hence compensating for short-term drifts.

For continuum observations, the receivers measure the total power received into a large bandwidth, and are switched to the calibration targets every 30 minutes to account for gain fluctuations.

Receiver Systems

The millimeter-wave receiver, shown schematically in Figure 3, is designed for continuum performance at 1.6-mm.

The 1.6-mm wave signal is down converted by mixing with a local oscillator (LO) signal at half its frequency in the subharmonic mixer. The resulting intermediate frequency (IF) is filtered and then detected for the total power continuum channel in the Intermediate Frequency Processor (IFP).

The submillimeter-wave receiver, also shown schematically in Figure 3, is designed for continuum performance at 0.5 mm and spectroscopic observation of three isotopes of water, ($H_2{}^{16}O$, $H_2{}^{17}O$ and $H_2{}^{18}O$), three methanol lines (CH_3OH), ammonia (NH_3), and carbon monoxide (CO).

The 0.5-mm wave signal is down converted to a first IF band of 5.5 to 16.5 GHz. A divider separates out the continuum band while the spectroscopic signal is further down converted for input to the spectrometer. The frequency synthesizers are used multiple times to save power. Nominally 20 MHz wide filters are used in the IFP before input to the spectrometer to eliminate excess noise. The bandwidth of the spectral line receiver will allow observations over Doppler shifts of ± 5.4 km/sec or ± 8 km/sec with frequency switching. This will allow short spectral observations of the asteroids near closest approach, and measurements of low velocity molecular clouds.

Spectrometer

Due to the narrow line-widths observed in cometary atmospheres from ground-based radio astronomy and the large number of expected molecular emissions within the passband of the radiometer, a multichannel spectrometer with a high-frequency resolution is required for the MIRO experiment. The Chirp Transform Spectrometer (CTS) is well suited for this task. Major progress in solid-state physics and photo lithographic processes have led to the availability of dispersive large-time-bandwidth Surface Acoustic Wave (SAW) filters. For situations in which high spectral resolution is required and the bandwidth of the analog input signal falls within the bounds of achievable SAW filters, CTSs offer the most efficient technique (in terms of size, cost, power consumption, real-time capabilities, and electrical and mechanical stability) for performing spaceborne heterodyne spectroscopy.

The spectrometer is connected to the output of the Intermediate Frequency Processor (IFP) which down converts only the parts of the submillimeter-wave receiver's first IF that are necessary. The spectrometer's function is to perform real-time spectral analysis of the down converted submillimeter-wave signals. The spectrometer output is a digitised power spectrum supplied to the Command and Data Handling System.

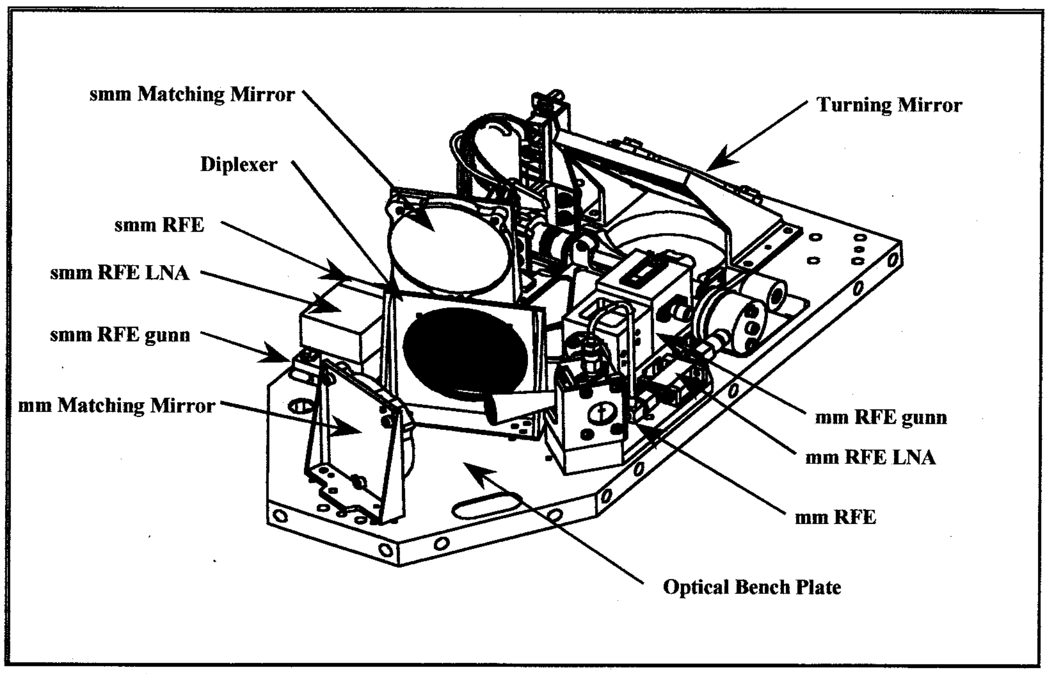


Figure 3 MIRO Optical Bench

Command and Data Handling

The Command and Data Handling (C&DH) system encompasses of all the electronics that control the operation of the instrument and communicates to the spacecraft via a serial port. The C&DH consists of the computer, flight software, engineering data electronics (EDE), and power supplies. The computer receives, processes, verifies, and executes all commands that control the operation of the instrument via the flight software. The C&DH directs the acquisition of science and housekeeping telemetry and formats the data in the appropriate packets. The EDE monitors selected temperature, voltage, and current levels within the instrument.

The selected flight computer for the MIRO is a radiation hardened Reduced Instruction Set Computer (RISC) System/6000 (also referred to as RS/6000) which was used on the Mars Pathfinder and Mars Surveyor Projects. The design of this computer is based on the Rios Single Chip (RSC) RISC microprocessor with implementation of the VMEbus and RS232 interfaces and it provides up to 128 Mbytes of local memory (RAM). The processor is a single chip implementation of the IBM Model 220 workstation and it is considered to be in the POWER PC architecture family. The two sides of the computer assembly are shown in Figure 4.

The 28-Vdc input from the spacecraft is converted into the various voltages needed by the instrument and distributed to the assemblies in the Electronics Unit and separately in the Sensor Back End Unit. There are a total of five power converters which were chosen not only for the voltages needed but to provide a clean grounding scheme for the instrument. There are three converters in the Electronics Unit and two in the Sensor Backend Electronics Unit.

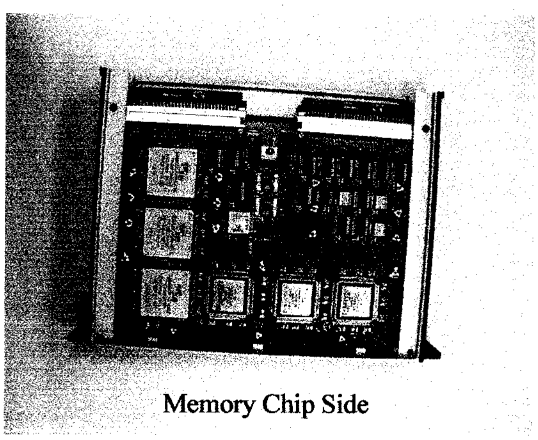
The Flight Software provides the control of the MIRO Instrument hardware to fulfil the MIRO Instrument science requirements. The top-level design represents the first step in the translation of requirements to a software system. The MIRO flight software consists of a start-up routine followed by a generic executive. The executive then activates Command and Data Handler, Data Collection and Transfer, Sequencing, Calibration, and Background Processor and these modules execute the appropriate routines for each required function. The major software component involves instrument algorithms developed for instrument calibration sequences, frequency switching, and continuum/ spectrometer modes under rather general conditions.

The data from continuum, spectroscopic, and calibration measurements is packetized and stored in a standard format. Information regarding instrument health, mode of operation and science data is stored and reported in the telemetry packets (CCSDS format as described in the ESA Telemetry Standard).

MIRO Operational Modes

The MIRO instrument is configured to have several operational modes to optimise capability for different power availability. An engineering mode provides a low power mode to obtain housekeeping measurements only. Single and dual receiver continuum modes are available to obtain the radiometric brightness within the MIRO field-of-view from the millimeter and submillimeter channels. They are also useful for the investigation of the properties of surfaces such as those of the asteroids and comet nucleus. A spectroscopic mode allows for the spectrometer and the submillimeter-wave intermediate-frequency (IF) signal processing to be on at the same time as the corresponding continuum channel. This spectroscopic mode allows a sensitive detection of specific gases generated by the comet nucleus (and possibly the asteroids as well).

In the comet rendezvous stage of the mission, MIRO will initially turn on in continuum mode and begin nucleus sounding measurements. During the cometary and targeted mapping phases, a majority of the viewing will be in the one or two receiver/spectrometer modes to study outgassing


Memory Chip Side

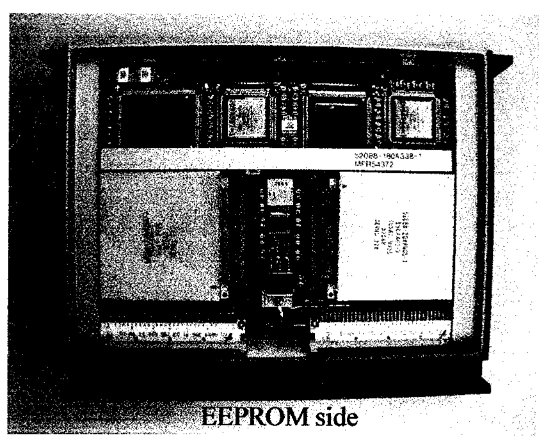

EEPROM side

Figure 4 MIRO RS6000 Computer

processes, bulk composition, and coma formation. These phases will provide the highest spatial resolution for studying the nucleus. If limb sounding is feasible, it will enhance the minimum detectability of species, and allow greater resolution of the coma.

Following the mapping phase, MIRO plans to operate in the two receiver/spectrometer mode. During this phase, both nucleus and coma studies will be performed.

3. Low Mass, Low Power, Low Cost and Performance?

Achieving the design described above was a major technical undertaking. To fit on a spacecraft bound for a comet, the instrument had to not only meet the scientific performance criteria but also be low mass and use much less power than traditional microwave instruments of the same capability. Additionally, in the faster, better, cheaper NASA environment, it had to be low cost. This last aspect was particularly challenging since the ESA requirements were not completely defined at the beginning of the program and, in fact, continued to be updated and changed even after the MIRO flight model had been fabricated and assembled.

Comparable instruments in the same general scientific class are usually heavy (over 100 kg), use a lot of power (150 Watts), and are expensive ($75 - $100 Million). MIRO's final specifications in this area were 20 kg, 65 Watts peak, and approximately $26 Million which includes over $6 Million from MIRO's European partners. To meet those numbers, MIRO made many design decisions to build in the ability to be a low mass, power and cost instrument.

Key to keeping all resource uses to a minimum was the decision to have only two receiver frequencies. This allowed the amount of structure and electronics to be highly optimized to meet the science objectives. A descope decision during the design phase also significantly reduced the mass and power required. Originally both receivers were to have continuum as well as spectroscopic capability. The final instrument has spectroscopic capability only in the submillimeter frequency.

In the mechanical area, an all aluminum structure was chosen to minimize mass. In the Sensor Unit, this approach also allowed the telescope to be easily athermalized. Exposed to the space environment, the telescope will operate at low temperatures (~100 K) at comet rendezvous to moderate temperature (~300 K) at perihelion. The aluminium structure also maximised performance over the large temperature range since the telescope scales with temperature to maintain a sharp focus. The optics were then designed to have an intermediate focus point near the internal turning mirror. This was ideal in making the warm optics inside the spacecraft insensitive to pointing conditions of the cold telescope structure as it expanded and contracted due to space environmental conditions. Lateral misalignments are minimised by symmetrical design in one axis and fixing the telescope mount near the beam axis through the baseplate.

To reduce structural mass, the instrument was also divided into four boxes. [The original concept was to have the entire instrument as one larger unit.] This provided significant mass savings, particularly in the baseplate assembly because the interface did not have as large a load to handle for vibration. Even though this decision increased the spacecraft interfaces by a factor of four, one for each unit, they were simple mechanical interfaces. Additionally, splitting the instrument into boxes provided a more efficient thermal path as each unit now had between 4 and 10 bolts across which to transfer its waste heat.

Microwave electronics are traditionally known for their large size and high power usage. The use of hybrid parts in these electronics reduced the mass and power needed for a microwave instrument. US companies have done much in recent years in developing electronics for communications technology. MIRO applied this technology for its' Intermediate Frequency Processor, Phase Lock Electronics, and Frequency Synthesizers. All of these components were designed and developed by commercial vendors and delivered to JPL for integration into the instrument.

The computer chosen for MIRO, the RS6000, was part of a common buy at JPL for several missions. Originally developed by IBM, the computer is now produced by BAE Systems in Manassas, VA. It has low mass (1.2 kilograms), and can operate between 5 and 20 MHz which allows optimzation for power conditions. MIRO chose to operate at 5 MHz. The power consumption of the RS6000 at that speed was less than 4 Watts. Participation in the common buy helped significantly reduce the purchased cost of the computer for the MIRO Project.

One of the final ways that MIRO was able to significantly reduce cost was to find extremely capable people and to use an approach where there was one person for multiple jobs. Even though this exposed the project to some risk in the personnel area, it did provide significant cost savings and allowed a more thorough integration of the functional areas. Each person had a "big picture" view of the instrument that streamlined interface negotiations in the beginning and enhanced the testing approach during final functional and performance tests.

4. Communication Processes and The International Team

Since the MIRO instrument was in a partnership with two non-US hardware providers, an efficient, smoothly running and frequent communications structure was required to ensure success. This structure and the information exchanged also had to conform to all appropriate US Customs and State Department rules.

The National Aeronautics and Space Administration (NASA), JPL, ESA, the German Aerospace Center (DLR), MPAe, Centre Nationale d'Etudes Spatiales (CNES), and the Observatoire de Paris first established Letters of Agreement that formalized the relationships and allowed the exchange of information within Customs and State Department rules. At the same time, an official Memorandum of Understanding between NASA and ESA was drafted. Within JPL, a review process was put in place with the International Relations office. This office is responsible for guiding each project through the maze of regulations to ensure that all Customs and State Department rules regarding information, hardware or software interchanges with a foreign country conform to regulations.

Once that was in place, the MIRO project instituted its communications infrastructure with three major objectives: (1) ensure understanding of all technical aspects of the instrument through frequent communication, (2) formalize the interfaces through electronic documentation, and (3) keep the cost low. An electronic library with passworded access for all team members was established to facilitate information exchange (internally as well as externally) and archiving of documents. Weekly telecons were set up with both the French and German participants to keep communication open and frequent. Individual phone calls and faxes were also used in abundance to ensure understanding on everyone's part. Electronic interface control documents for mechanical and electrical interfaces were created. All of these approaches kept the flow of information going and allowed a significant cost savings over the traditional method of communication with a non-local partner: the face-to-face meeting. This is not to say that meetings never occurred on MIRO. They were limited though to approximately three per year and generally included science meetings as well as exchanges with the ROSETTA Project management. The meetings were therefore encompassing yet efficient methods of exchanging information in a very limited time frame.

5. MIRO AND JPL PROCESSES

Development of MIRO began in 1996 as one new JPL process was already in its infancy. During MIRO's development cycle, two other major process initiatives within JPL were begun. All of these had major impacts on the instrument development.

The JPL Design Hub

MIRO was the first project within JPL to use the new Design Hub (DHUB) Process. This approach to development had two parts – common, centralized software hosting facilities and co-location facilities. The idea behind the DHUB was to lower the development costs for projects by spreading major software package costs over a larger population and providing early co-location facilities for small projects in the earliest stages of design. MIRO was a small project so it could take advantage of the co-location facilities. This greatly facilitated communication interchanges and enhanced development of interfaces between the major functional areas of the instrument.

Using the common software had a mixed effect. From a mechanical viewpoint, the cost impact was neutral since the old JPL process had been migrated into the DHUB. For optical development, MIRO actually contributed to the software capability because no standard microwave design packages were available. MIRO's need drove a design effort within JPL with verification of the design process and software being provided by MIRO itself. In the area of the Command and Data Handling electronics, the DHUB had a negative effect. This was due to the fact that the capability of the software tool set available was much greater than that required by MIRO. Therefore the costs in this area began to exceed that initially estimated. This was corrected during the transition from engineering to flight model fabrications. Changes that needed to be included in the flight model due to engineering model test data used a different and much less expensive tool set to implement. This simpler software has since been incorporated into the DHUB as one of the available tools.

The JPL Design Principles

One of the results of the investigation into the Mars spacecraft failures was the development of a set of guidelines called the JPL Design Principles. Many of these principles address resource margins and design approaches that apply over a broad set of missions. They are not construed as requirements. However, lack of compliance with the Design Principles requires a review and approval by JPL management. This is to ensure that the project will still be successful despite non-compliance with accepted engineering practice for spacecraft and flight instrumentation. This set of guidelines was applied to all current projects, including MIRO.

The impact on MIRO was additional internal review for compliance to the Design Principles. This necessitated some justification since MIRO did not comply with all of the principles, particularly in the margin resource area. The lack of compliance was due to ESA's management approach to margin and reserve – the spacecraft held all margin and reserve above an instrument's current best estimate (CBE) – as opposed to the NASA JPL approach which is to allocate margin to a subsystem. The ESA approach limited the MIRO's flexibility in the design process but provided the spacecraft with very detailed information regarding any changes the instrument made since CBEs were reported monthly.

ISO Quality Standards

The other major initiative within JPL that impacted MIRO was the adoption of the ISO Quality Standards. Although MIRO's level of formal documentation was very high due to ESA's requirements for the ROSETTA program, JPLs implementation of ISO added requirements for specific documents and reviews. This burdened an already jam-packed development schedule. To minimize the impact, MIRO managers implemented most of the requirements documents with review by the working engineers. In addition, the managers designated themselves as first contact for the reviews to handle most questions with follow up interviews occurring when necessary with team members. MIRO was chosen several times for ISO audits. The approach developed by MIRO management worked and MIRO received very high marks from ISO auditors, both internal and external, for the thoroughness of its documentation and processes implementation.

6. The Politics of Programmatics

One of the most challenging aspects of implementing MIRO was the balance of responding to the technical and management requirements from ESA while being funded by NASA. While NASA mandates a faster, better, cheaper approach, ESA embraces a style of implementation more akin to that used on previous JPL missions such as Galileo and Cassini. That style has a very rigid approach to development and testing in addition to extremely heavy documentation requirements. MIRO had to negotiate many requirements to ensure that the budget provided by NASA would cover all of the development. Additional issues also arose because the complete set of requirements was not available at the beginning of the ROSETTA program. These issues, in addition to significant development problems with some of the MIRO assemblies, impacted the program. Therefore, the MIRO management team was only partially successful in being able to control costs. In addition to spending reserve money to solve the development problems, money also had to be spent on meeting ESA implementation requirements. This resulted in cost overruns that necessitated a funding augmentation for MIRO. With those funds, MIRO successfully completed the flight hardware fabrication and delivered the instrument to the ROSETTA spacecraft for integration and test. Currently, the instrument is undergoing testing on the ROSETTA spacecraft as part of its Assembly, Test and Launch Operations tasks.

7. Summary

The Microwave Instrument for the ROSETTA Orbiter is a highly capable microwave instrument that will investigate comet WIRTANEN as part of ESA's ROSETTA program. Conceived in NASA's faster, better, cheaper, environment, the development of MIRO had many challenges during its development.

Key decisions were made early in the project to optimize the science while controlling technical resources. This enabled early conceptualization and partitioning of the design. This was especially significant in reducing mass and power. At JPL, new management processes were incorporated and used to MIRO's advantage during the development.

The international aspects of MIRO provided management challenges. Communications processes were established to ensure successful technical development. These contributed substantially to MIRO's success. Requirements negotiations, though, necessitated an approach that balanced technical and management issues against cost. This activity required an extensive amount of time and effort by the MIRO management team.

From a cost perspective, it was learned that a very conservative reserve posture should be carried for this type of development. Not only did technical problems arise, but it is also acknowledged that in general, international collaborations carry some cost.

The development of MIRO has shown that a small, low cost, lightweight, low power microwave instrument with good technical performance can be developed. MIRO's development has opened the door for inclusion of this type of instrument on spacecraft investigating planetary and other small bodies.

Acknowledgments

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Cynthia L. Kahn joined JPL as an engineer in June of 1980. She has been involved primarily with instruments for planetary flight projects. Currently, she is the MIRO Systems Engineer and the Project Element Manager for MIRO Electronics, Software, Integration and Test. She has held this position since November 1996.

Ms. Kahn was the Cassini Imaging Science Subsystem (ISS) System Engineer and Calibration Manager from February 1990 through November 1997. As System Engineer, she was responsible for all system engineering functions, including requirements definition, resource management, design analysis, modeling and verification. As the Calibration Manager, she defined, negotiated with the science team, and then implemented the calibration plan for the ISS. She also coordinated all analysis and reporting of the data.

Prior to that, Ms. Kahn held various technical and management positions at JPL in optical engineering and proposal management.